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Submarine Hydrothermal Ore Deposits

by

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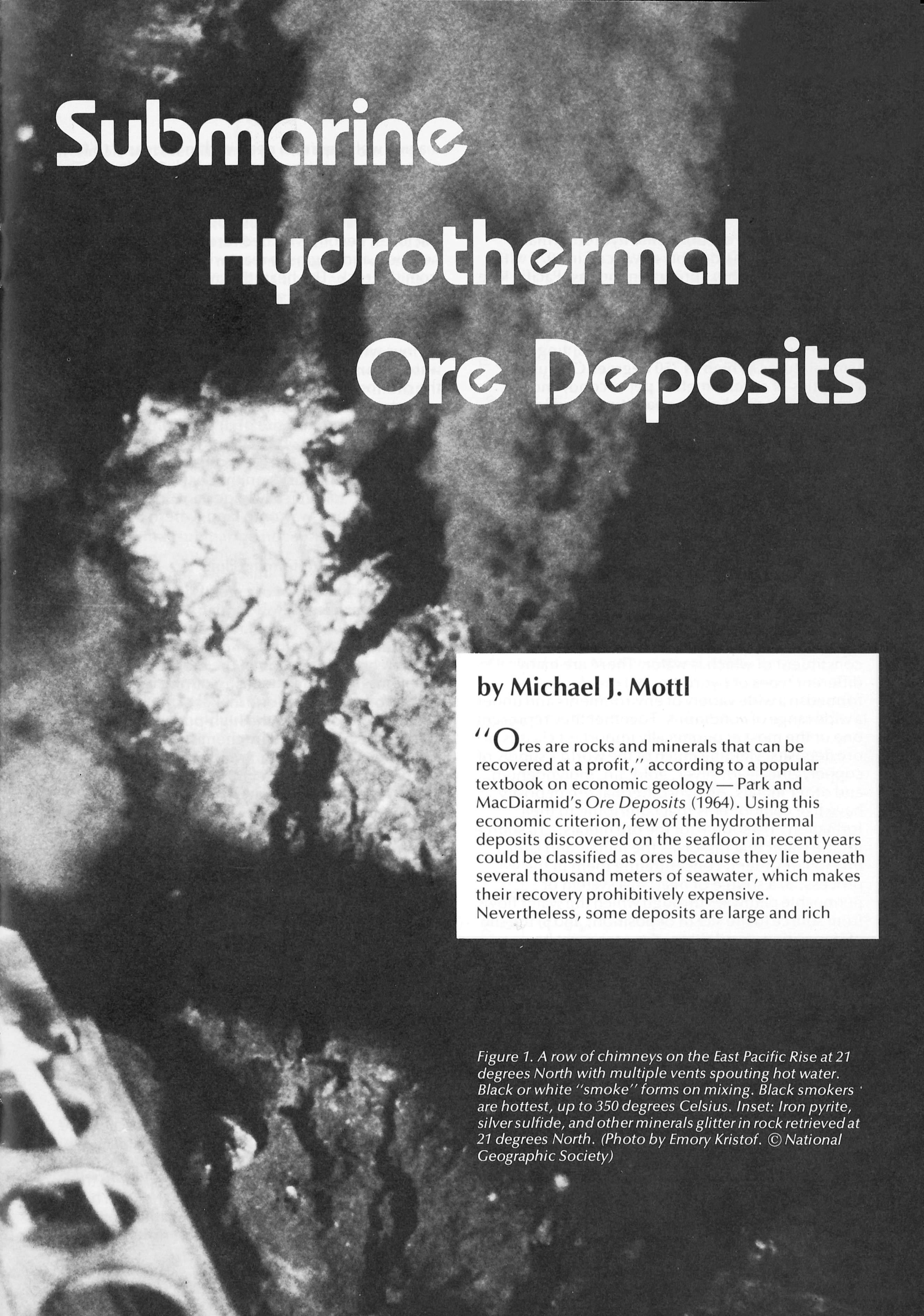


by Michael J. Mottl

"Ores are rocks and minerals that can be recovered at a profit," according to a popular textbook on economic geology — Park and MacDiarmid's *Ore Deposits* (1964). Using this economic criterion, few of the hydrothermal deposits discovered on the seafloor in recent years could be classified as ores because they lie beneath several thousand meters of seawater, which makes their recovery prohibitively expensive. Nevertheless, some deposits are large and rich

Figure 1. A row of chimneys on the East Pacific Rise at 21 degrees North with multiple vents spouting hot water. Black or white "smoke" forms on mixing. Black smokers are hottest, up to 350 degrees Celsius. Inset: Iron pyrite, silver sulfide, and other minerals glitter in rock retrieved at 21 degrees North. (Photo by Emory Kristof. © National Geographic Society)

enough to be exploitable, and those that are not promise to be profitable in another way by increasing our understanding of how hydrothermal ores form so that we can locate them more easily in the future.

The study of submarine hydrothermal deposits was considerably advanced in 1979 with the discovery of hot springs on the East Pacific Rise at 21 degrees North. Unlike the warm springs discovered a few years ago on the Galápagos Spreading Center (see *Oceanus,* Vol. 20, No. 3, p. 35), these springs are *hot!* They are venting water at temperatures as high as 350 degrees Celsius at velocities of several meters per second, and are precipitating prodigious quantities of sulfide ore, minerals rich in copper, zinc, and iron. The precipitates form chimneys around the individual vents that spout black or white smoke composed of precipitated crystals of sulfides and other minerals (Figure 1). The discovery is easily the most exciting and significant in this field since the discovery of the Red Sea hot brines and metal deposits (see *Oceanus,* Vol. 22, No. 3, p. 33).

Hydrothermal Ore Deposits

Hydrothermal refers to hot water: hydrothermal deposits are deposits that have formed by chemical precipitation from hot solutions, the principal constituent of which is water. There are many different types of hydrothermal ore deposits, formed in a wide variety of environments and under a wide range of conditions. Together they represent one of the most economically important classes of ore deposits, yielding much of the world's supply of copper, zinc, lead, silver, gold, tin, molybdenum, and other metals. All hydrothermal ore deposits have five components that contribute to their formation: 1) a source for the ore metals; 2) a source for the water that dissolves the metals and later precipitates them, concentrating them in the process; 3) a source of heat; 4) a system of permeable pathways through which the water flows from source to the site of deposition; and 5) the site of deposition. In addition, the ores must be deposited in a setting that allows them to survive (for perhaps millions of years) the ravages of weathering, erosion, and other processes that would tend to disperse the metals. Variations in these five components, along with differences in the physical and chemical conditions experienced by the hot solution as it travels from its source to the site of deposition, account for the great variety of hydrothermal ore deposits exploited today.

The submarine environment provides a unique combination of components for the formation of hydrothermal deposits. By far the most abundant source of heat in this setting is that associated with the formation of new oceanic lithosphere along the mid-ocean ridge system, where the seafloor is spreading apart and basaltic magma wells up from deep within the earth to form new ocean crust (see *Oceanus,* Vol. 17, No. 3). The new crust becomes highly fractured as a result of the tensional forces that pull the lithospheric plates apart. Seawater percolates down through the fractures, becomes heated through contact with the hot rock, and begins to react with it, leaching metals from the rock. The heated seawater, now chemically modified and carrying dissolved metals, is less dense because it is hot, and so tends to rise. It ascends to the seafloor, exiting as submarine hot springs whose waters mix with the ocean bottom water. Thus, for submarine hydrothermal deposits, the ore-forming solution is usually modified seawater, the source of metals is the rock of the ocean crust, and the site of deposition is on or within the seafloor. This combination of circumstances has and is producing a variety of hydrothermal deposits on the seafloor, as well as a number of economically important analogues that have found their way onto land, where they are being mined.

Seawater as an Ore-forming Fluid

The concentrations of ore metals in most natural waters are extremely low, and in normal seawater they are especially so. In fact, concentrations in seawater are so low that simply measuring them accurately has been one of the most difficult problems in marine chemistry during the last 30 years. For example, if one makes artificial seawater in the laboratory from the high-purity "reagent grade" chemicals used by chemists, it will have 100 to 1,000 times the concentration of heavy metals found in natural seawater!

In order for seawater or any other natural water to become an ore-forming fluid, some minimum concentration of ore metals in solution is required. This is because a metal deposit must be fairly large before it becomes profitable to mine. The minimum size for a deposit to be considered ore is an economic question. The total tonnage of ore in a given deposit depends on how long it took the deposit to form and how fast the hydrothermal solutions were able to transport metals to the site and deposit them there. The latter depends, in turn, on the flow rate of the hydrothermal solution, its total concentration of dissolved metals, and the efficiency with which the metals were precipitated as the solution passed through the site of deposition.

For seawater to become an ore-forming fluid, its ore metal concentrations must be increased by a factor of about 20,000 or more. As stated earlier, the most abundant source for these metals is ocean crust. The problem is to get the metals out of the rock and into the seawater, and to keep them there at high enough concentrations until they can be precipitated in a restricted locality. Laboratory experiments on the solubilities of various ore minerals and metals show us that there are three principal ways to increase the concentration of metals in an aqueous (water-rich) solution in contact with rock — increase its temperature (and pressure), increase its salinity, or decrease its pH, that is, make it more acidic. The first two of these methods are known to be important for submarine hydrothermal deposits; the third is an intriguing hypothesis awaiting confirmation in a natural setting.

The temperatures reached by seawater circulating through newly formed oceanic crust at a mid-ocean ridge may be estimated in several ways. Rocks dredged from fault scarps in these submarine mountain chains indicate from their chemistry, mineralogy, and oxygen isotopic composition that they have been altered by seawater at temperatures ranging from a few degrees to 600 degrees Celsius, with the bulk of the high-temperature alteration occurring at 200 to 300 degrees Celsius (see *Oceanus,* Vol. 19, No. 4, p. 40).

The first submarine hot springs discovered along a mid-ocean ridge, those at the Galápagos Spreading Center, were emitting water at only 20 degrees Celsius, but the chemistry of this water indicated that it had reacted with basalt at 350 to 400 degrees Celsius (Corliss and others, 1978; Edmond and others, 1979). Then came the discovery of the 350 degrees Celsius springs on the East Pacific Rise; the chemistry of this water is presently being analyzed in John Edmond's laboratory at the Massachusetts Institute of Technology (see *Oceanus,* Vol. 23, No. 1, p. 33).

Figures 2 and 3 show the concentration of iron and manganese in seawater that reacted with basalt for many months in laboratory experiments at high temperature. Also shown are data from the seawater-fed hot spring at Reykjanes, Iceland. Iron and manganese, while less important as ore, are much more abundant in both rocks and solution than are copper, zinc, and other ore metals. All of these metals can be expected to show the large increase in concentration with temperature (and pressure) shown in the figures. Note that the largest increase occurs above 350 degrees Celsius. For altered seawater solutions such as these that have normal salinity and are neither strongly acid nor strongly alkaline, 350 degrees Celsius represents the *minimum* temperature at which seawater is likely to become an ore-forming fluid.

Compared to the solutions responsible for most known hydrothermal ore deposits, seawater is quite dilute, having only 3.5 percent total dissolved salts. Typical ore solutions, as deduced from studies of minute amounts of solution trapped in ore minerals, range in salinity from 3 to 50 percent. The second way to turn seawater into an efficient metal-transporting agent is to increase its salinity. This mechanism is largely responsible for producing the only true hydrothermal ore body

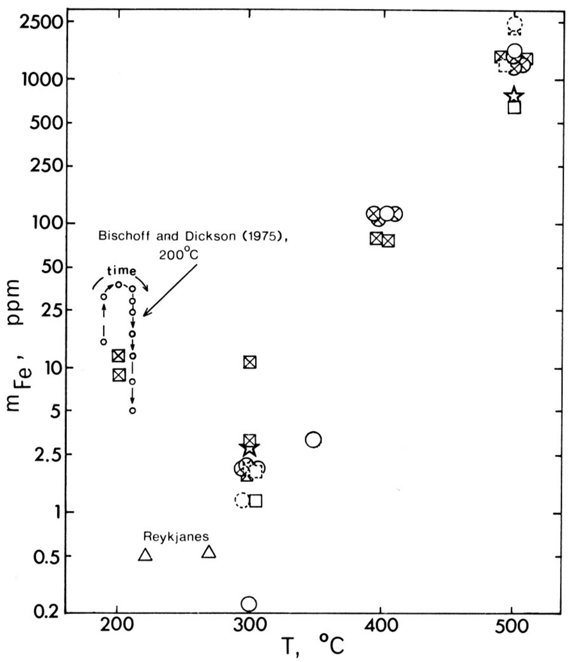


Figure 2. Concentration of iron in solutions produced by reaction of seawater with basalt in laboratory experiments and in the geothermal system on the Reykjanes Peninsula of Iceland (from Mottl and others, 1979).

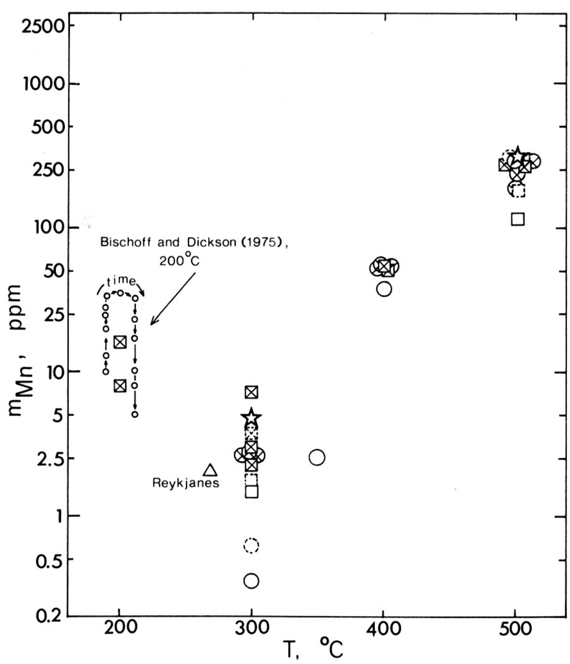


Figure 3. Concentration of manganese in solutions produced by reaction of seawater with basalt in laboratory experiments and in the geothermal system at Reykjanes, Iceland (from Mottl and others, 1979).

discovered so far in the oceans: the deposits in the Atlantis II Deep and in other nearby basins along the spreading center in the Red Sea. As elsewhere along the mid-ocean ridge system, the source of the hydrothermal solutions is seawater, the heat is derived from the seafloor spreading process, and the metals are leached from the crustal rocks. What makes the situation in the Red Sea unique is that the hot, circulating seawater encounters not only volcanic rock during its subterranean travels, but also salt — huge deposits of it, several kilometers thick. These deposits of predominantly halite (NaCl, common table salt) formed when the Red Sea was younger and narrower than it is today. The salt deposits formed by evaporation of seawater in the long, narrow new ocean basin when its outlets to the rest of the oceans were constricted or closed.

Halite is extremely soluble, especially in hot solutions, so these deposits are readily dissolved into the circulating seawater, increasing its salinity to about nine times that of normal seawater. The resulting hot brine has a much greater capacity for transporting ore metals in solution because most of these metals readily combine with the chloride ion, Cl^-, in solution to form highly soluble neutral or charged complex ligands, such as $FeCl^+$, $CuCl^0$, and $ZnCl^0_2$; these complexes form in greater abundance at higher temperatures and chloride concentrations. Thus, the Red Sea hot brines contain high concentrations of manganese, iron, lead, zinc, copper, cobalt, silver, and other metals.

The third method for dissolving high concentrations of metals in seawater is by lowering its pH, which is the same as raising the hydrogen ion (H^+) activity in solution. As anyone knows who has spilled battery acid on his car, metals tend to dissolve readily in acid (H^+-rich) solutions. Experiments at Stanford University four years ago led to a startling discovery: ordinary seawater, when heated to high temperature (greater than 250 degrees Celsius), has a built-in mechanism for becoming a highly acid hydrothermal solution (Bischoff and Seyfried, 1978). As temperature increases, seawater becomes saturated with and precipitates a previously unknown and as yet unnamed mineral containing magnesium, sulfate, and hydroxyl (OH^-) ions. Magnesium and sulfate are two ubiquitous constituents of sea salt, whereas the hydroxyl ion comes mainly from the water itself: $H_2O = H^+ + OH^-$. This reaction coupled with removal of OH^- from solution into the new mineral produces free H^+, making the hot seawater very acid (pH 3.5 at 350 degrees Celsius). Such an acid solution is very corrosive to the surrounding rocks and readily attacks them, leaching metals into solution. This reaction with the rocks tends to consume the H^+ and also to convert the Mg-OH-SO_4 mineral into common Mg-OH-silicate minerals, such as clays. Whether the hot seawater remains acid depends on the relative rates of the H^+-producing and H^+-consuming reactions. These depend, in turn, on how fast seawater flows through the submarine hydrothermal system, compared with how fast it reacts with the rocks it flows through. If flow rates are more rapid, then extremely metal-rich hot spring solutions can be produced (Figure 4).

Although such highly acidic hot springs have yet to be discovered, plans are being formulated to explore the area where they are most likely to occur: along the East Pacific Rise south of the equator. This area of the seafloor contains the most extensive hydrothermal deposits known to exist in the oceans. The deposits are predominantly iron and manganese oxides that have accumulated four to thirty times faster than the normal rate for the deep oceans. Mixed in with normal deep-sea sediment, they are a few meters to a few tens of meters thick and extend from about 10 to 30 degrees south, covering an area of 625,000 square kilometers.

The Seafloor as a Depositional Environment

An ore deposit is by its very nature a *concentration* of metals. Even most ore-forming solutions have lower concentrations of metals than the rocks from which the metals were leached. Thus, most of the real concentrating gets done at the site of deposition by processes that remove the metals from solution. If an ore deposit is to be formed, these processes must operate efficiently and over a restricted area, removing metals from a very large volume of solution as it passes through. Otherwise, in the absence of a depositional environment with suitable characteristics, the solution will simply distribute the metals over a wide area once again.

The common feature of depositional environments for hydrothermal ore deposits is their ability to produce a rapid and drastic change in those properties of the solution which keep the ore metals dissolved in the first place — temperature, pressure, salinity, and pH. Another important property is the degree to which the solution is oxidized. Rapid and drastic changes in these properties can cause the metals to be "dumped" from solution, whereas more gradual changes cause them to be precipitated slowly over a larger area. Thus, slow cooling of a hydrothermal solution as it ascends toward the surface, by loss of heat to the surrounding rocks, is less likely to produce an ore deposit than is the rapid cooling that would result from a sudden pressure drop, or from mixing with another, cold solution. As for a sudden change in pH, this is most likely to occur when the hydrothermal solution encounters either another, more alkaline solution, or a different type of rock, such as a calcareous marine sediment, and reacts with it. A third mechanism for raising pH is boiling,

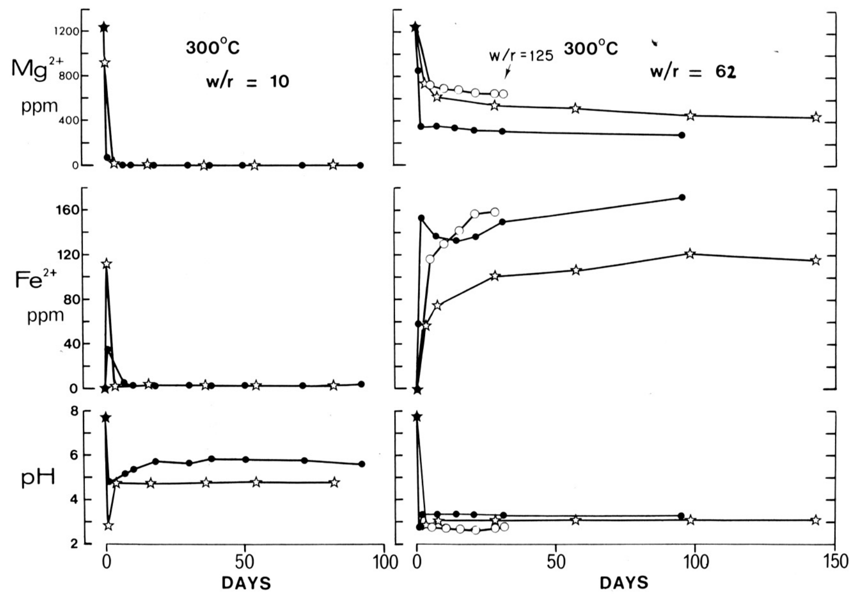


Figure 4. Concentrations of magnesium and iron and pH with time in solutions from five experiments reacting seawater with basalt. The two experiments on the left used low water/rock ratios and simulate flow that is slow relative to reaction. The three on the right, at high water/rock ratios, simulate flow that is fast relative to reaction (from Mottl and Seyfried, 1980).

accompanied by loss of acid-forming gases such as carbon dioxide.

A depositional environment must have two other properties if it is to produce an ore deposit— it must be stable and remain in one place long enough for a sizable amount of ore to accumulate there, and the ore must be preserved there after deposition until it can be discovered and exploited.

Most submarine hydrothermal activity is likely to occur along the mid-ocean ridge system. In this setting, boiling is unlikely to occur because of the high pressure from the 2 to 3 kilometers of overlying seawater. Reaction of hydrothermal solutions with marine sediments will be the exception rather than the rule, as sediment is normally very thin or absent altogether on such very young crust. One process for precipitating metals from hydrothermal solutions, however, is virtually inevitable in any submarine setting: mixing of the solution with ocean bottom waters. As hydrothermal solutions are normally hot, slightly acid, and reducing, whereas normal seawater is cold, slightly alkaline, and oxygen-rich, mixing of one with the other produces a drastic and nearly instantaneous change in the chemical and physical conditions in solution. The dramatic result can be seen in Figure 1, which shows the plume formed by rapid, turbulent mixing of a 350 degrees Celsius metal-rich hydrothermal solution with 2 degrees Celsius bottom water on the East Pacific Rise. The black smoke consists of iron, copper, and zinc sulfide minerals that have precipitated on mixing.

Submarine Hydrothermal Deposits

To date, no submarine hydrothermal deposit has been sufficiently studied that all components contributing to its formation are known. Nevertheless, the data at hand suggest some intriguing relationships among known deposits along mid-ocean ridges, pointing out the importance of special situations in producing and preserving large deposits. A review of known deposits illustrates this:

East Pacific Rise, 21 degrees North. The spectacular discovery in 1979 of hot springs near the mouth of the Gulf of California was presaged by the finding the previous year of spire-like chimneys composed of ore-grade zinc, copper, and iron sulfide minerals in the same locality (CYAMEX, 1979). These deposits were discovered by the French submersible *Cyana* during the joint French-American-Mexican CYAMEX expedition, and were associated with extinct hydrothermal vents. When the RISE expedition returned in 1979 with the submersible *Alvin,* operated by the Woods Hole Oceanographic Institution (WHOI), and found the active vents, it was learned that *Cyana* had missed them by at most a few hundred meters, a fine example of the difficulties of search in the deep sea!

All of the active vents discovered occur along a very narrow zone, 100 to 200 meters wide, close to the axis of the spreading center. The RISE expedition observed 25 temperature anomalies associated with active vents over a 6-kilometer-long

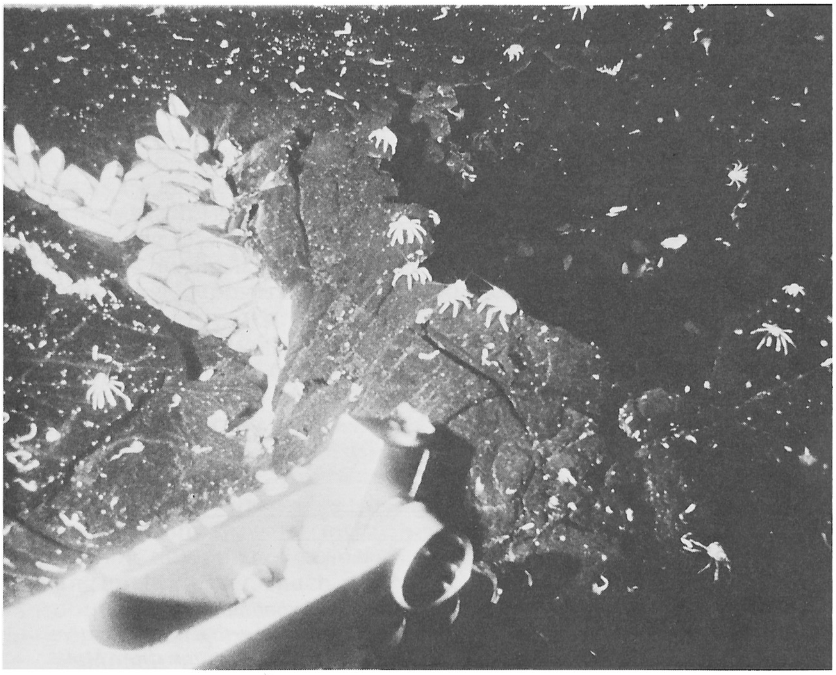


Figure 5. Warm water vents on the East Pacific Rise at 21 degrees North are similar to those found along the Galápagos Spreading Center. Water at about 20 degrees Celsius flows out from among the rocks, supporting a diverse biological community, including crabs and foot-long clams.

segment of the ridge crest (RISE, 1980). The vents range from the very high-temperature type (Figure 1) in the southwest to much cooler, Galápagos-style vents (Figure 5) in the northeast. The cooler vents are emitting water at 23 degrees Celsius or less and are surrounded by diverse colonies of unusual marine life, including giant clams and tubeworms, crabs, limpets, and an eel-like fish, which depend upon the chemically nurtured bacteria that grow in the vents for their food source. The very high-temperature vents, by contrast, are too hot for living creatures, but even they are quickly colonized in their cooler regions by worms, crabs, and eel-like fish.

The most distinctive features of the high-temperature vents are the chimneys. Most of the chimneys are a few meters tall, but some are as high as 10 meters. They are composed almost entirely of sulfide minerals often arranged in concentric zones (Figure 6), with minor amounts of sulfate and silicate minerals and silica. The chimneys are spaced a few meters apart within elongated vent fields, and typically rise from a mound composed of debris broken from the chimneys themselves. These mounds rest directly on basalt, as there is little or no sediment on such young crust (less than 20,000 years old). The chimneys are spouting either "black smoke," composed of sulfide minerals, or "white smoke" composed of pyrite (iron sulfide), barite (barium sulfate), and silica.

While these deposits are certainly ore-grade (up to 50 percent zinc, 6 percent copper, 0.05 percent silver) and are forming in spectacular fashion, they are not large or extensive. Forming as they do on the open seafloor, they are immediately subject to oxidation and partial dissolution. Exposed to oxygen-rich bottom waters, they are unlikely to survive as sulfides beyond the sediment-free limits of the axial valley. Thus, their depositional environment is favorable to formation of a small deposit, but not to its preservation.

Of greater interest as potential ore bodies are the metal sulfides that may be deposited *within* the seafloor in this setting. Observations made from *Alvin* on a return trip in November, 1979, indicate that vents with temperatures of 350 degrees Celsius are depositing both copper and zinc, whereas vents at 273 and 295 degrees Celsius are depositing only zinc. For the latter vents, copper is probably precipitating within the crust as the solutions cool during ascent. Equally intriguing is the possibility that the Galápagos-style vents in this locality are much cooler than the "smokers" because they have mixed with cold seawater *within* the crust, at shallow levels, rather than above it in the bottom waters. This would shift the site of ore deposition to a more protected location. The chemistry of the Galápagos warm springs suggests that this is indeed happening.

Galápagos Spreading Center. No hydrothermal deposits have been recovered from

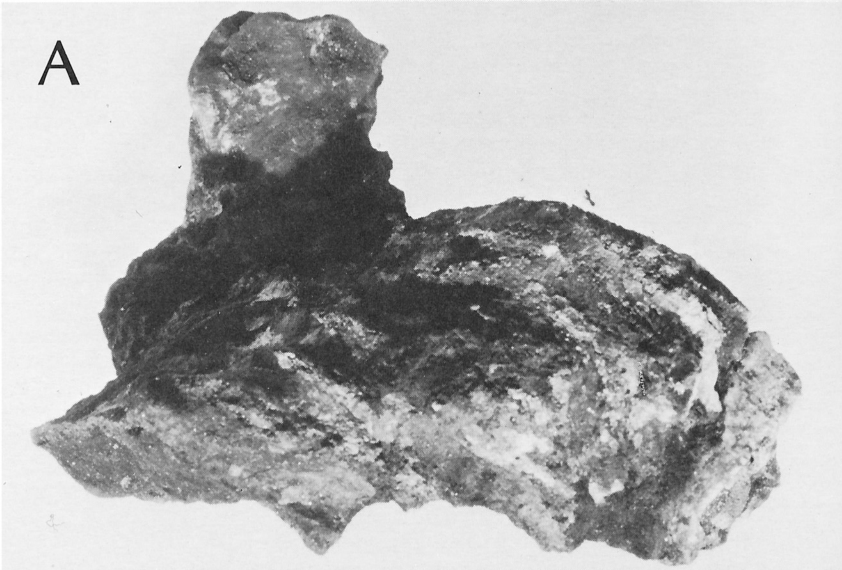
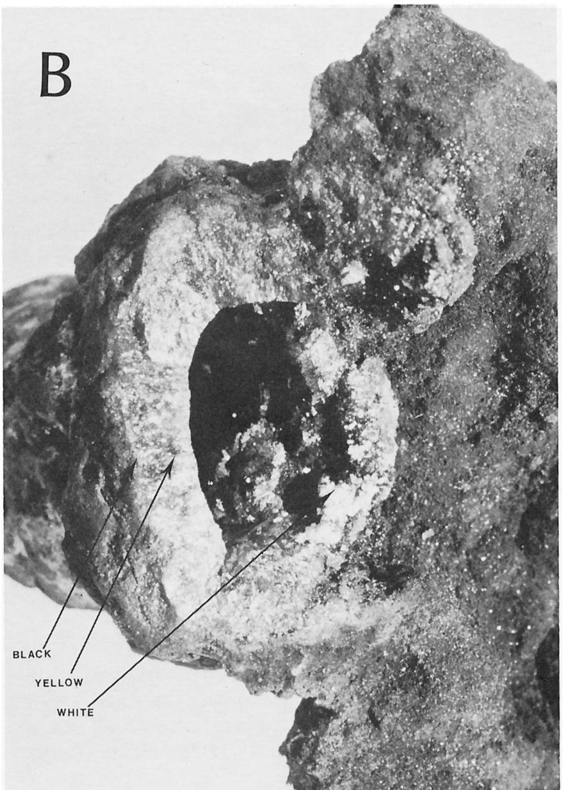


Figure 6. Two views of a chimney from the East Pacific Rise at 21 degrees North. A: Side view of 15-centimeter high chimney, which was spouting hot water at 350 degrees Celsius when sampled in November, 1979. Chimney, at left, protrudes from a base of massive sulfides. B: View of same sample looking upward through chimney. Center of chimney is hollow and is lined with chalcopyrite, $CuFeS_2$. Inner yellow zone is chalcopyrite and pyrite, FeS_2. Outer black zone is wurtzite, ZnS, and pyrite. White patch near center of photo is anhydrite, $CaSO_4$, and talc, a hydrated Mg-silicate. (Photos by Marjorie Styrt)



the crest of the Galápagos Spreading Center, where the first warm spring vents were discovered and sampled in 1977. Features that appear to be extinct sulfide chimneys have been photographed but not sampled. Nonetheless, comparison of the chemistry of the warm spring water with that from laboratory experiments indicates that the warm water results from shallow subsurface mixing of cold seawater with a 350 to 400 degrees Celsius, metal-rich hydrothermal solution. Thus, one can imagine the precipitation processes observed on the East Pacific Rise at 21 degrees North occurring *within* the seafloor at the Galápagos, forming a well-protected ore deposit.

Metal deposits, mostly iron silicates and manganese oxides, do occur 25 kilometers south of the Galápagos Spreading Center, where they form mounds protruding from the sediment. Precipitation of the metals here is mediated by reaction of the hydrothermal solution with normal marine sediments, as the solution emanates from long fractures in the underlying basalt.

Mid-Atlantic Ridge. The best-known deposit here is from the TAG hydrothermal area at 26 degrees North, discovered in 1970 by the Trans-Atlantic Geotraverse project. This deposit is pure manganese oxide. The TAG area may be similar to the Galápagos in having extensive shallow subsurface mixing. The chief unknown in this area is the temperature, and therefore metal content, of the hydrothermal end-member solution involved in mixing. If high, an ore deposit may be forming within the crust here as well. Plans have been made to visit this area with *Alvin* in 1982.

East Pacific Rise, 10 to 30 degrees South. These extensive, rapidly accumulating sediments, rich in iron and manganese oxides, have already been mentioned in discussing seawater as an ore-forming fluid. The remarkable thing about these deposits is their great volume, which implies a much larger input of hydrothermally-derived metals than elsewhere along the mid-ocean ridge system. Whereas the sulfide deposits at 21 degrees North on the East Pacific Rise are highly localized, these deposits blanket about half of the total area of new ocean crust along this part of the ridge, which is spreading at an abnormally rapid rate. Presumably the high metal input is related to the fast spreading rate, but exactly how or why is not known. Perhaps the hot springs here, none of which have yet been discovered, are hotter or more acidic than elsewhere.

Another interesting question concerns the mineralogy and chemistry of the deposits. Are sulfides forming here, as at 21 degrees North, which are then oxidized to oxides and hydroxides by prolonged contact with ocean bottom waters? If so, why are these deposits so relatively poor in zinc and copper? Do rich deposits of zinc and copper lie on and within the crust in this region? If so, they may be analogous to the copper deposits on Cyprus. These deposits are among the earliest known to have been exploited — they were worked for copper ore as early as 3000 B.C., and were mined extensively by the Romans for centuries. They are still yielding copper today. The deposits are located within a slab of ocean crust that was thrust onto the land when Europe collided with Africa millions of years ago. Similar deposits occur in Newfoundland, Turkey, and Oman.

Red Sea. As the only genuine hydrothermal ore deposit found so far in the oceans, the Red Sea heavy metal deposits deserve special mention. The unusual metal-transporting properties of the hot brines have already been discussed. What remains is to describe the special depositional environment created by these highly saline hydrothermal solutions. These solutions exit from the seafloor at about 100 degrees Celsius, along the floor of deep fault-bounded basins. Although the solutions are hot, they are denser than normal seawater because of their high salinity, and so do not rise and mix readily with bottom waters. Instead, they remain within the deep basins, which are thus filled with dense, metal-rich brines at a temperature of about 56 degrees Celsius. The metals precipitate within the basins, producing sulfide, silicate, and oxide minerals, depending on the local chemical environment within the brines. Because of their density, the brines are able to create a special and unusual depositional environment for the ores. Mining of these ores by a West German firm that will employ giant submarine "vacuum cleaners" is about to begin.

Manganese Nodules. The other submarine ores that promise to be mined eventually are manganese nodules, potato-size nuggets of manganese and iron oxides rich in nickel, copper, cobalt, chromium, and other metals (see *Oceanus*, Vol. 21, No. 1, p. 60). Manganese nodules are not hydrothermal deposits. Rather, they accumulate slowly by chemical precipitation from normal seawater, in regions of the seafloor with slow sedimentation rates. A long-standing controversy, nonetheless, has been whether nodules contain some amount of metal derived from a hydrothermal source. Figure 7 shows that manganese derived from the warm spring vents along the Galápagos Spreading Center is easily detectable in otherwise normal ocean bottom waters. This effect can be seen at least 250 kilometers from the ridge (Bolger, and others, 1973). This kind of evidence has revived the controversy over the source of metals in the nodules, in at least some areas where the nodules occur.

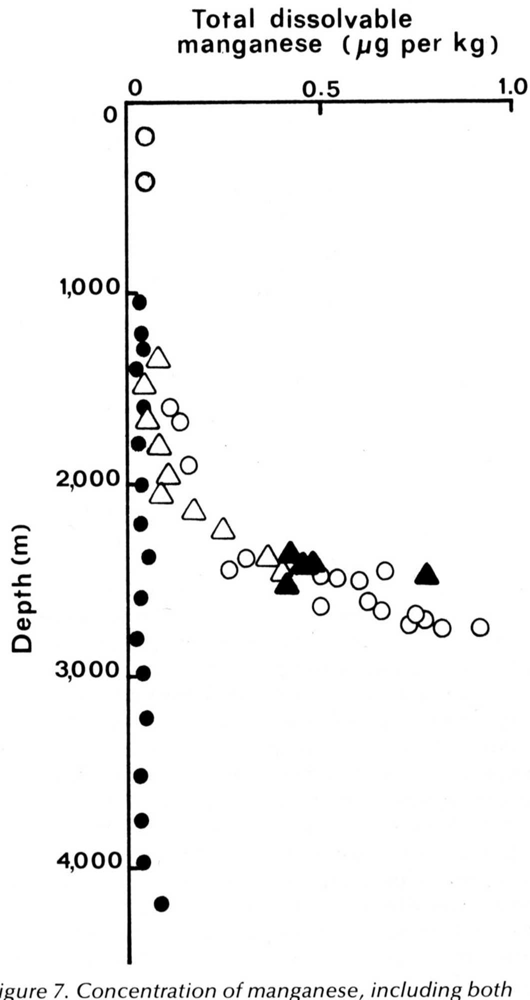


Figure 7. Concentration of manganese, including both dissolved and particulate, in seawater from the open Pacific (closed circles) and from the Galápagos Rift (open circles and triangles) (from Klinkhammer and others, 1977).

Other Environments. While most hydrothermal activity in the oceans occurs along the mid-ocean ridge system, this is not the only submarine environment where such processes take place. Two particularly promising non-ridge environments where ore deposits may be forming under the sea are the diffuse spreading centers that create marginal seas behind island arcs, such as the Sea of Japan, and the bases of the volcanic island arcs themselves. While hydrothermal processes here will be similar to those at mid-ocean ridges in most respects, two factors make them potentially different. First, the molten magmas that form and erupt in these environments have a much higher content of water from the earth's interior dissolved in them than do the characteristically dry magmas (less than 1 percent H_2O) at mid-ocean ridges. Some of this water, which would be acid and metal-rich, may be involved along with seawater in forming metal deposits in these environments. These water- and silica-rich magmas also are more likely to erupt explosively than are mid-ocean ridge lavas, fracturing the hot young rock and allowing ready access for seawater. Second, the more silica-rich rocks formed from these magmas are richer in some metals, notably lead, than are basalts. Thus, ore deposits formed here would be lead-zinc-copper deposits. A noted example of submarine island-arc ore deposits is the Kuroko ores of Japan. Similar ores occur in the Philippine Islands, Fiji, Tasmania, Canada, and possibly Turkey.

What the Future Holds

The discovery of the East Pacific Rise hot springs has spurred tremendous interest among the oceanographic community. Plans are now being made to launch a four-year, multi-institutional project to explore the East Pacific Rise for additional areas of hot spring activity and ore deposition. The major objective of the program will be to examine the nature of hydrothermal processes along the mid-ocean ridge system from the slow-spreading to the very fast-spreading segments, such as at 10 to 30 degrees South. The project will involve the use of surface ships; deeply towed instrument packages, such as Scripps Institution of Oceanography's Deep Tow and WHOI's *Angus* sled; new high-precision multibeam echo sounding for making highly accurate topographic maps of the seafloor; and ultimately manned submersibles, including *Alvin*. I think it is fair to say that this rewarding field of research is about to experience a veritable explosion of information, which cannot help but improve our understanding of how, where, and why an important class of metallic ore deposits forms.

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